Application of Computed Radiography (CR) for Characterization of Historical Documents

Marko RAKVIN [1], Andreja DRAGOJEVIĆ [2], Damir MARKUČIČ [1]

[1] Faculty of mechanical engineering and naval architecture, University of Zagreb; Zagreb, Croatia
Phone: +385 1 6168 364, Fax: +385 1 6168 466; e-mail: mrakvin@fsb.hr, dmarkucic@fsb.hr
[2] Croatian conservation institute; Zagreb, Croatia; E-mail: adragojevic@h-r-z.hr

Abstract
Watermarks and paper structure are significant properties of historical documents that allow historians and restorers possibility of dating where and when a particular paper was produced. Because of the document content (text, graphics etc.), it is sometimes difficult or even impossible to determine the layout of the watermark and paper structure using only light transmission technique. In that case, radiography can be used as an alternative method. In this paper the possibilities of using computer radiography (CR) for watermark extraction and paper structure characterization as well as advantages and disadvantages over conventional film radiography are discussed. Optimization of CR radiographic parameters (selection of imaging plates and radiation sources) for low-voltage X-ray and electron transmission technique was conducted and the results were compared to light transmission technique findings.

Keywords: cultural heritage, computed radiography, electron radiography, watermark, paper structure, imaging plate

1. Introduction

From the beginning of paper production outside the Arabic world in the 13-th century, European paper manufacturers were adding characteristic watermarks into the paper as a guarantee of quality and sign of recognition for their products. Watermarks were fabricated in the way that metal wire formed symbol was placed on the paper making sieve, so after the linen pulp was oozed, pressed and dried, on the location where metal wire symbol was positioned paper was thinner. Because of that, watermarks can be seen if viewed under the bright light. Research in the field of filigranology showed that every manufacturer used specific symbols for watermarks, as well as sieve construction, in a certain time period. Identifying the watermark and sieve construction allows historians to date when and where the paper was manufactured.

Common techniques that are used to identify paper watermarks are: transmitted light photography, photosensitive paper technique, low voltage (soft) X-ray, beta radiography, electron transmission radiography. The advantage of using electron emission radiography for watermark identification is that, unlike transmitted light photography and low voltage radiography, content of the paper (text, graphics ect.) do not reveal on the radiogram enabling reliable identification of features of interest. Conventionally, “classic” slow AgBr industrial radiographic film is used for this purpose.

Today, AgBr film are increasingly being replaced by variety of radiographic techniques that produce digital radiographic image based on various detector and readout technologies [1]. In the paper, the possibility of using electron transmission and low voltage X-ray computed radiography (CR) using industrial unmodified BaFBr imaging plates was investigated. Previous research demonstrated that BaFBr imaging plates with absence of protective overcoat polymer layer can be used as a detector for investigation of paintings with electron transmission radiography [2]. Due to the properties and construction of imaging plates, exposure times and intensifying effect of radiographic lead foils differs from those obtained when using radiographic film. To date, images on radiographic films still achieve better spatial resolution than that obtained by imaging plates, but imaging plates have far greater dynamic range allowing more information to be seen on a single digital radiographic image.

For this reason, in order to achieve adequate image quality for watermark and paper characterisation, exposures were done on two types of imaging plates and varying radiation sources. Some of the presumed benefits of using computed radiography instead of classic film radiography for watermark identification and paper characterisation also include less exposure dose, no need for darkroom environment and computer aided interpretation and analysis of the resulting digital radiograms.
Research was obtained on a copper etching artwork that shows a saint St. Vasily on front side (Figure 1a) and a text written in old-slavic language on the back side. Dimensions of the paper are 348 mm x 220 mm and the thickness is 0.17 mm. Given that the artwork startled a lot of different information such as Greek letters on the graphics and old-slavic text on the back, it was interesting to investigate the origin of the paper as an information carrier.

a) b)

Figure 1. Inspected document a) front side – copper etching artwork; b) back side

2. Radiography of paper and artwork

The most common approaches for paper and artwork radiography are:

- low voltage (soft) X-ray radiography,
- beta radiography and
- electron transmission radiography.

2.1 Low voltage X-ray radiography

Low voltage radiography of paper is based on variation of absorption of X-rays of different areas of paper due to variations in paper thickness, density or compositions. Since these variations are usually very small low voltage X-rays are used to obtain sufficient radiographic contrast on the radiogram. Use of 4 to 7 kV X-rays in combination with slow radiographic film is recommended [3]. Metallic pigments that are present as a design on a paper will also be visible on the radiogram. If film cassette is used, such low energy radiation will create an unwanted image of the cassette on the radiogram. For that reason, radiation sensor must be in direct contact with test object. This is often a problem when using radiographic film as a detector, because of the light contamination risk of the film. Accordingly, exposures must be done under darkroom safelight environmental conditions. In case of computed radiography, when imaging plates are used as a detector, because of their lesser sensitivity to visible light, exposures can be done under subdued light conditions. Also, imaging plates are more sensitive to low energy radiation than radiographic film, making them potentially particularly suitable for this kind of application.

2.2 Beta radiography

Beta radiography technique uses “beta-plates” as a source of beta particles radiation. They consist of radioactive isotope ^{14}Cembedded in a thin sheet of polymethyl methacrylate. ^{14}C isotope emits only beta particles of relatively low energy (150 keV) that are sufficient to penetrate approximately 250 mm of air, 0,3 mm of skin or a sheet of paper [4]. Such plate is positioned in direct contact over examined paper and the radiogram is recorded on a radiographic film. Activity of such plate is very low, in order of 100 mCi/g, so exposure times are relatively long. Exposure times are long, almost reaching 8 hours. Thin layers of organic and metallic pigments usually do not appear on the radiograph, leaving the resulting image free of paper design content. Results that are obtained by this technique are unsurpassed when it comes to resulting image quality of the watermark and sieve footprint. Electron transmission radiography is possible substitution for this method.

2.3 Electron transmission radiography

Since quantum dose efficiency of conventional radiographic films decreases with photon energy increase, radiographic lead foils in direct contact with detector are used to enhance it when high energy X-rays or gamma radiation (over 100 keV) is used as a radiation source [5]. When such lead foil is exposed to X-ray or gamma photons it undergoes an internal photoelectric effect. As a result, there is an increased amount of “free” electrons inside the Pb foil. Surface photoelectrons that are able to escape the foil and exceed to the detector, irradiate it, and this results in signal intensifying

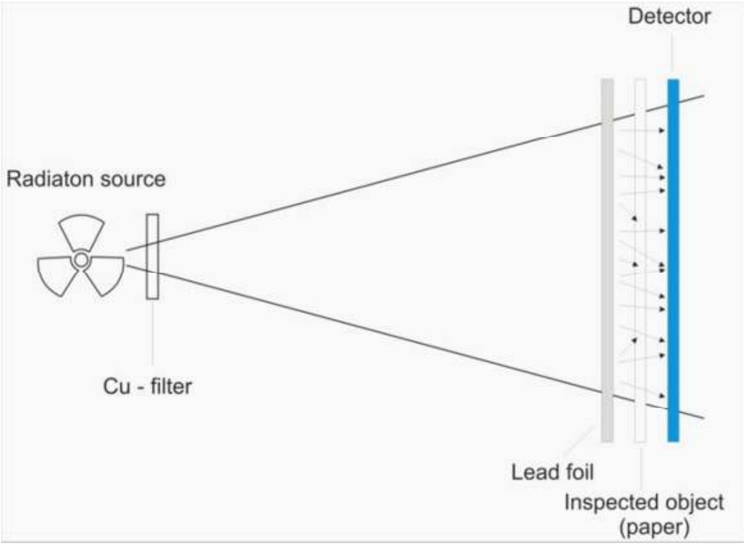


Figure 2. Setup for electron transmission radiography of paper

Electron transmission radiography setup is shown by Figure 2. In this technique, intensifying effect of the lead foil commonly used in industrial radiography is the main principle of radiographic image forming. Inspected object (paper) is placed between lead foil and the detector. Tight contact between lead foil, inspected object, and detector is essential. The electron emission from lead foil is diffuse, and the electrons are further diffused as they pass through the specimen. Therefore, space between foil, specimen, and detector has a negative impact on the radiographic image sharpness. High energy X or gamma rays are used (greater than 220 keV) [3] to cause photoelectric effect in lead foil due to which photoelectrons emit from foils surface. During the transmission through the inspected paper they are partly absorbed by the inspected paper depending on the paper's thickness and density, and the (latent) image is formed on the detector. Because of low quantum dose efficiency of high energy photons, they pass through detector causing only slight overall fogging of the radiographic image. The greatest disadvantage of using film for this application is that handling and radiographic exposure must be done under darkroom (safelight) conditions, as opposed to the imaging plates used in CR that will not be affected by the low light levels. On the other hand, intensifying effect from the emitted photoelectrons is less pronounced when using imaging plates due to their construction. Because imaging plates are reusable, they have a thicker polymer protective overcoat than radiographic films. This causes less photoelectrons to reach the photosensitive BaFBr layer [6]. For this reason, higher energy radiation, than in case of radiographic film, must be used to achieve generation of photoelectrons of sufficient energy to penetrate inspected object and imaging plate’s protective overcoat to form the latent image in photosensitive layer.

3. Experimental setup

To explore the capabilities of using conventional industrial CR system for paper watermark identification and characterization, two radiographic techniques were employed:

- low-voltage (soft) X-ray transmission radiography and
- electron transmission radiography.

For low-voltage X-ray transmission technique industrial small focus X-ray tube was used and for electron transmission radiography conventional industrial X-ray tube and radioactive isotope ^{192}Ir were employed in combination with Kodak Industrex Flex general GP (general purpose) and XL Blue (high resolution) imaging plates for industrial application. Exposures were done under the dim light (20 lux). Standard cassettes for imaging plates were not used. In ordered to provide sufficient contact between inspected object and detector when electron emission radiography was preformed, 5 mm acrylic polymer plate was placed on top of the lead foil.
Equipment used for the experiment and radiographic parameters are stated in Table 1.

Table1. Equipment and radiographic parameters

<table>
<tr><th>Technique</th><th>Low-voltage X-ray transmission</th><th>Electron transmission radiography</th></tr>
<tr><td rowspan="2">Radiation source</td><td rowspan="2">ISOVOLT 160 M2-small focus 0.4</td><td>Baltospot GM 300 D</td></tr>
<tr><td>Ir 192</td></tr>
<tr><td>Detector (Imaging plates)</td><td colspan="2">Kodak Industrex Flex GP & XL Blue (350mm x 430 mm);
no cassette</td></tr>
<tr><td>CR Scanner / scanning parameters</td><td colspan="2">VMI 5100CR /
Laser power - 15 J/m^2; Scanning resolution – 50 µm ;
Photomultiplier tube voltage – 5.25 V</td></tr>
<tr><td rowspan="2">Source energy / Radiographic exposure / Source to detector distance (SDD)</td><td rowspan="2">4 kV; 12 mA/min / 800 mm</td><td>300 kV; 18 mA/min / 700 mm</td></tr>
<tr><td>222 GBq; 12.5 min / 700 mm</td></tr>
<tr><td>Lead foil</td><td>-</td><td>0,027 mm</td></tr>
<tr><td>Filtration</td><td>1 mm Be (inherent)</td><td>3 mm Be (inherent) + 12 mm Cu</td></tr>
<tr><td>Software</td><td colspan="2">Starrview 7 ; Isee!</td></tr>
</table>

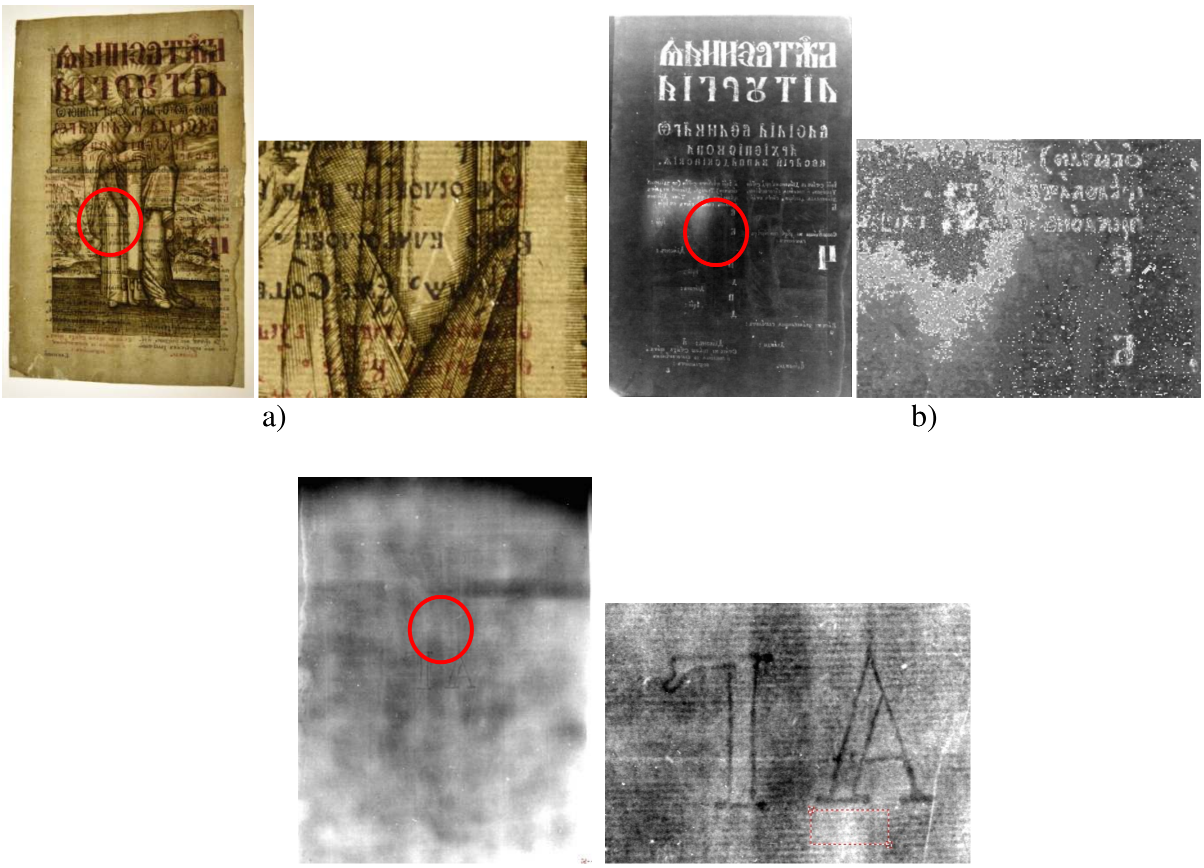
Scanned xry files were exported as 16 bit tif files and processed by means of image analysis software ISee!.

4. Results

Obtained results of the inspected document by means of three different techniques to identify watermark and sieve construction imprint are presented in Figure 3. On every image the region of interest, where the watermark is located, is marked with red circle. Magnified images of the region of interest are attached to the main images.
Figure 3a is a photograph of the watermark taken with a light transmission technique on the light table. Contours of the watermark are only partially visible as brighter lines. Text and graphics interfere with the signal response from the watermark so it cannot be clearly discerned and characterised as well as sieves imprint.

Figure 3b is a CR digital image of the examined area of the document obtained with low-voltage X-ray transmission radiography on the Blue XL imaging plate. Watermark outline, due to low achieved radiographic contrast, is hardly visible. Opposing to the black letters, red letters found on the document are shown on the digital radiographic image, so it is assumed that red dye contains heavy metal (Pb) pigments in its composition. Contours of the copper etched artwork are also visible as is the damage on the document edges.

Figure 3c is a digital radiographic image obtained with electron transmission technique using CR and XL Blue imaging plate. From watermark identification standpoint, this technique resulted with best differentiation feature and image quality. Watermark outline and sieve imprint can be clearly distinguished and seen. Since content of the document cannot be seen on the radiographic image, there are no obstructing elements interfering with the watermark layout. Also, damage on the document edges is visible.

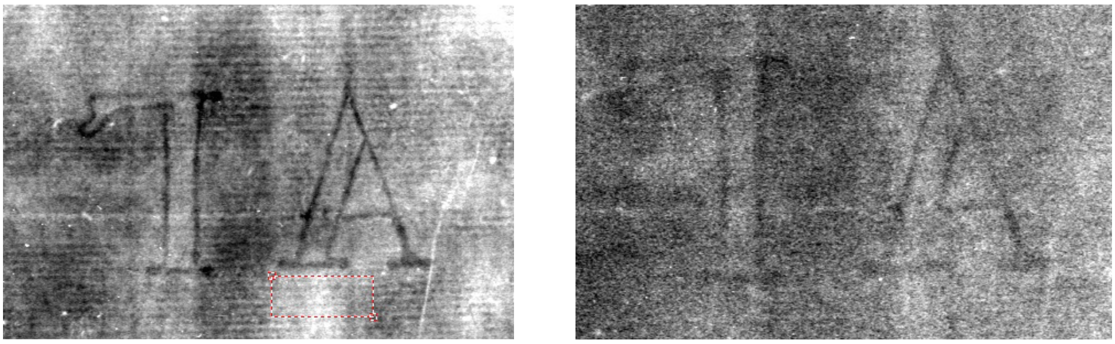


a) b)

c)

Figure 3. Recorded images of inspected document: a) light transmission technique, b) low-voltage X-ray CR, c) electron transmission CR

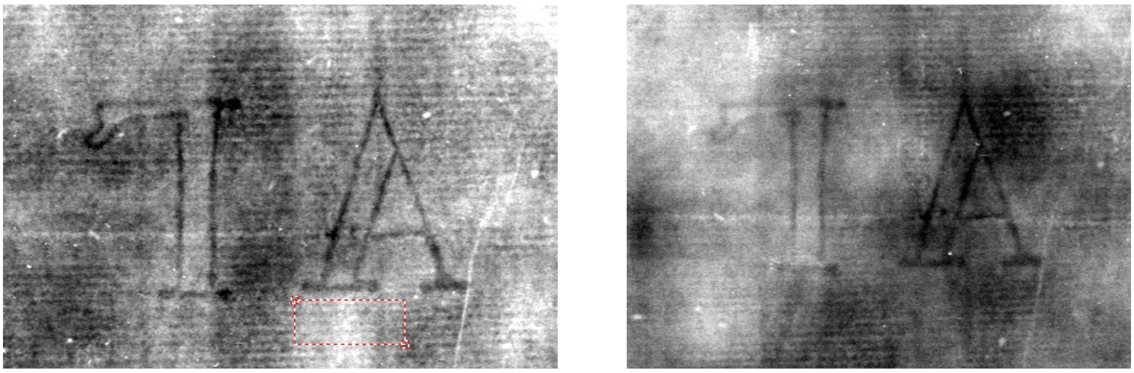
Influence of different radiation source energy used for CR electron transmission technique is shown in Figure 4. Better image quality, regarding spatial resolution and radiographic contrast, is achieved when X-ray tube at 300 kV voltage was used (Figure 4a) rather than ^{192}Ir (Figure 4b) as a radiation source. Both exposures were done on the same XL blue imaging plate. While watermark outline is still visible on a digital radiographic image obtained with ^{192}Ir, sieve imprint is not so well distinguished. This occurrence is attributed to general better quality of X-ray radiation in comparison with the radiation produced by radioactive isotopes.



a) b)

Figure 4. Influence of radiation source on image quality for electron transmission CR: a) X-ray tube (300 kV), b) ^{192}Ir

To determine influence of imaging plate type on the electron transmission CR image quality, exposures were conducted on two types of imaging plates: Kodak GP and Kodak XL Blue. Results are presented by Figure 5. While achieved radiographic contrast was not influenced by imaging plate type, spatial resolution was decreased when GP imaging plate was used instead of high resolution XL Blue plate.



a) b)

Figure 4. Influence of imaging plate type on image quality for electron transmission CR: a) Kodak Industrex Flex XL Blue, b) Kodak Industrex Flex GP

5. Conclusion

Watermark and sieve imprint on historical documents are valuable information carriers about origins of the historical document as well as for tracing and dating of historical technologies and productions. For this reason it is valuable to identify and characterise them as precise as possible. As it is inherent for NDT practice, different methods and techniques applying different excitation principles, consequently obtain different signal responses while interacting with the inspected object regarding to the subject (object) contrast.

In this paper three different approaches to watermark and sieve imprint identification and characterisation on historical document were compared: light transmission photography, low-voltage CR and electron transmission CR. It was established that electron transmission radiography produced most suitable results, for this particular purpose, due to absence of distracting elements on recorded (radiographic) image while retaining relevant information about watermark and sieve layout.

It is also shown that industrial CR with unmodified BaFBr imaging plates as a radiation detector could be successfully used instead of conventional film radiography for radiographic testing of paper documents with low-voltage X-ray transmission technique and electron transmission technique.

From all preformed techniques and parameter variations carried out in this research, best image quality was obtained by means of electron transmission computed radiography using high resolution imaging plates (Kodak XL Blue) as a radiation detector in combination with high energy X-ray tube as a radiation source.

Acknowledgement

Procurement of the VMI 5100 CR system at the Laboratory for NDT at Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb was funded by Ministry of Science, Education and Sports within the research project #1201767-1763, "Reliability of non-destructive testing methods".

We are thankful to the Aeronautical Technical Center in Velika Gorica and ZIT d.o.o. for providing an X and gamma ray sources for the exposure of test samples.

References

1. M Körner, C.H. Weber, S. Wirth, K.J. Pfeifer, M.F. Reiser and M. Treitl, Advances in Digital Radiography: Physical Principles and System Overview, RadioGraphics, Vol. 27, No 3, pp 675–686, 2007.
2. O. Schalm, L. Vanbiervliet, P. Willems and P. De Schepper, Radiography of paintings: Limitations of transmission radiography and exploration of emission radiography using phosphor imaging plates, Studies in Conservation, Vol. 59, No. 1, pp 10-23, 2014.
3. C. F. Bridgman, Radiography of paper, Studies in Conservation, Vol. 10, No. 1, pp. 8-17, 1965.
4. T. Inada, K. Kawashima, K. Hoshino, and H. Matsuzawa, Energy Spectra of Electrons Emerging from Lead Exposed to 320 kVp White X-rays, Japanese Journal of Applied Physics, Vol. 2, No.2, pp 99–105, 1963.
5. R.A. Quinn and C.A. Sigl, Radiography in Modern Industry. Rochaester, NY: Eastman Kodak Company, pp 168–172, 1980.
6. J. Beckmann, S. Rachny, U. Zscherpel and U. Ewert, Improved Procedure for Computed Radiography - A Comparative Study on Welded Tube Sections by Film Radiography and Computed Radiography, 17th World Conference on Nondestructive Testing, Shanghai, China, 2008
7. N. Ash, Recording watermarks by beta-radiography and other means. In: The Book and Paper Group Annual, vol.1. American Institute for Conservation of Historic and Artistic Works, Washington, 1982
8. J. Lang, and A. Middleton, Radiography of Cultural Heritage, 2nd ed. Oxford: Elsevier Butterworth-Heinemann, 2005.